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FACULTY OF GRADUATE STUDIES

The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Plugging Effect of Bacteria in Sandstone Systems", submitted by Tibor Fekete, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science in Petroleum Engineering.

UNIVERSITY OF ALBERTA

THE PLUGGING EFFECT OF BACTERIA IN SANDSTONE SYSTEMS

THESIS

Presented to the Faculty of Graduate
Studies in Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

Department of Chemical and Petroleum Engineering

By

Tibor Fekete, B.Sc.
Edmonton, Alberta
November, 1959

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A B S T R A C T

The plugging effect of bacteria was investigated by injecting various concentrations of both dead and living bacteria cells through sandstone cores. Pressure profiles along the cores were recorded periodically during the injection cycles.

The plugging effect was analyzed using a plot of the ratio of reduced permeabilities to the initial permeability versus input volume. Results indicated that permeability has little effect on plugging while the concentration of bacteria in injection water has a significant effect on plugging characteristics. No difference was observed in the results obtained when using dead or living bacteria. The pressure profile curves showed that penetration of bacteria occurred throughout the core but that the greater part of the bacteria accumulation was in the first few centimeters at the input end of the core.

INTRODUCTION

Injection of water into oil producing formations has been applied in the petroleum industry in water flooding and in salt-water disposal. The first application of artificial water flooding was in the Bradford field in Northern Pennsylvania, about 1896, when efforts were made by scattered producers to develop flood conditions that would increase the yield of their properties. Introduction of water into oil reservoirs was illegal at this time. Opinion varied among early operators on the merits of water flooding, and it was twenty-five years later when the process was legalized by the Pennsylvania legislature. Since that time water flooding has become recognised in the industry as an important secondary recovery method in petroleum reservoirs.

From a physical point of view, water flooding operations may be considered simply as an extreme form of delayed pressure-maintenance operations. In fact, in contrast to the more common type of so-called "pressure-maintenance operations", which generally result only in pressure decline retardation, with an incomplete replacement of the space voidage created by the fluid withdrawals, there is usually some build-up of reservoir pressure in secondary recovery water injection. In the case of "water flooding" the rate of fluid injection, if conducted on a major scale, generally exceeds the volumetric withdrawals virtually throughout the whole course of the operations.

The water to be used for injection may be taken from a surface source, such as rivers, lakes, springs; or it may be fresh water produced through wells from shallow subsurface sources. Brines have also been used, produced through wells from deep seated sources, and in near coastal fields sea water has been used.

An ample supply of water must be made available for successful application of the water-flooding process, and the water used must not contain sediment or dissolved substances that will clog the pore spaces of the reservoir rock about the injection wells, or react with connate water in the reservoir rock to produce chemical precipitates, or cause swelling of clay particles, resulting in clogging of pore spaces and drainage channels. Any of the above phenomena would cause decreased water injection rates possibly resulting in less oil recovery. Some of the most effective plugging substances are bacteria. Several types of micro-organisms are capable of living in surface waters and in salt water produced from deep sources.

Sulfate Reducing Bacteria: These bacteria are small curved, rod shaped, or spiral organisms occurring in soil, sewage, fresh water, and sea water. They belong to the genus Desulfovibrio. Although the organism is essentially anaerobic it is apparently capable of growth in environment of several parts per million of oxygen and is not killed by continuous aeration for over a week.

The ability of sulfate reducers to remove hydrogen is a cause of anaerobic corrosion. Under aerobic conditions, iron

undergoes corrosion by a galvanic process where ferrous ions are formed at the anode and hydrogen ions are formed at the cathode. Atmospheric oxygen then transforms the hydrogen to water and corrosion proceeds. Sulfate reducers remove and utilize the hydrogen formed at cathodic areas of metals, reducing sulfate to sulfide, and subsequently increase the rate of the corrosion process anaerobically. The products formed are hydrogen sulfide and insoluble ferrous sulfide. Water injection pressures may rise considerably due to plugging effects from these products.

Iron Bacteria: These bacteria possess an extraordinary capacity for abstracting iron from waters and depositing it in their outer sheath, where it quickly oxidizes to ferric hydroxide. The genus Crenothrix starts life as a simple, nearly spherical, non motile cell which divides by fission and forms a chain, with the cells elongating in this process. These cells exude a mucilaginous tubular sheath which hardens and becomes impregnated with ferric hydroxide. Iron bacteria can grow without any organic substance, utilizing mineral salts and carbon dioxide. Tremendous amounts of yellow or reddish-colored slime can be deposited by iron bacteria, originating in the ferric hydroxide surrounding the bacteria. The slime masses can clog pipelines and seriously lower injection rates by sloughing off into water and plugging the formation.

Algae: These are simple forms of plant life. Typical large green growths are often seen in reservoirs and ponds.

Algae contain the green coloring matter chlorophyll and require sunlight as a source of energy in order to carry out photosynthesis, the manufacturing of complex energy-bearing substances, such as sugars and starch. Copious algae growth can lead to severe plugging, especially in open-water treatment systems. Their detrimental activity is greatly reduced in a closed system water-treatment installation.

The purpose of this study was to determine the damaging effect of these bacteria cells to the oil reservoir and to bring attention to the importance of eliminating them from the injection water. Very little work has been done on this problem. The work reported herein studies the plugging characteristics and the penetration depth of a given type of bacterium cells in sandstone cores of various permeabilities.

REVIEW OF LITERATURE

The first scientific report on this problem was prepared by Merks (1) in 1943, who worked for the Degree of Master of Science on the effect of bacteria on the permeability of oil reservoir rocks. His work included the analysis of field waters in order to determine the types of bacteria existing in the samples. A radial flow system was used to determine the plugging characteristics in limestone and sandstone cores of iron bacterial water, of sulfur bacteria and algae in Lulingfield water and of untreated and treated East Texas Field salt water. Sandstone cores showed greater plugging than limestone cores. An examination of cores revealed that a colloidal substance was present and was apparently clogging the pore spaces of the sand. This phenomenon was called the "silica effect" and was associated with every sand core used in the laboratory. The silica dissolved by the water hydrolizes and is precipitated as H_2SiO_3, which is colloidal silica acid.

Beck (2) reported in 1946 on the role of bacteria in oil production. All untreated Bradford input waters were found to contain common aerobic water bacteria. These bacteria accumulated on the sand face causing a decrease in water input rate.

In 1947 Beck (3) published an extensive paper on the prevention of micorbiological growths in water flood operations. In connection with his research he found, that the plugging material formed a filter cake on a porous disk (permeability 300 md) which was composed of about 60% organic matter. He pointed out, that bacteria may selectively plug the tighter sand.

DESCRIPTION OF MATERIALS

CORES

The cores used in this study were cut from a surface outcrop of Berea sandstone which is well consolidated, fairly clean and uniform grained. The sandstone was cut into cores 2.5 centimeters in diameter and 7-9 centimeters in length, using a laboratory core cutting technique with fresh water as the cutting fluid. The cores were mounted in plastic tubing to prevent liquid by-passing. Loose cores were placed into 2.5 cm I.D. Lucite tubing. Sealing was accomplished by heating to 120°C under 500 psis pressure in an oil bath. To provide a means to measure the pressure inside of the core during the experimental runs three pressure taps were drilled through the plastic well to the surface of the sample at equal spacings.

INJECTION WATER

It would have been impossible to analyze the role of every type of bacteria on water injection due to the difficulties encountered in culturing them under laboratory conditions. Therefore the micro-organism called Bacullus subtilis was used. This organism is characterized by its rod shape and is a spore bearing bacteria with an average size of 4μ in length and 1μ in width. This type of bacteria can be found almost universally in the soil, water and air, and is therefore commonly encountered in injection water.

It is spore forming and as such very resistent to chemical methods of treating of injection water. In addition the spores are resistent to temperature elevation such as occurs at the bottom of injection wells. When not producing spores it inclines to grow in chains. Masses of these chains can augment the plugging of the formation. In this respect it resembles the iron bacteria. The growth of this organism is frequently accompanied by slime formation. The organism itself is of the same size as the majority of microorganisms commonly found in injection waters.

It was necessary to maintain constant concentrations with respect to time to obtain conclusive data, therefore all of the bacteria were killed by using an autoclave method. One experimental run was made with the same live bacteria.

In order to exclude the plugging effect of any other material, distilled water was used as the carrier of the bacteria cells.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

DESCRIPTION OF APPARATUS

The linear permeability apparatus used in this series of experiments is shown in Figure 1. The entire process was conducted in a constant temperature cabinet. A vacuum pump was used to remove dissolved air from the system which, if present, could have led to false results. A pressure regulator between the apparatus and the compressed air source maintained the desired operating pressure.

The liquid storage reservoir for the air free water contained a free running piston, equipped with leather cups to prevent air by-passing, to transmit the driving force necessary for injecting water through the core. The settling of bacteria cells was prevented by a magnetic stirrer. Pressure gauges connected to the core measured the injection pressure at the input end of the core and the pressures at the pressure taps along the core. A calibrated cylinder and stop watch were used to determine the flow rate. All connecting lines were plastic with brass fittings.

DESCRIPTION OF PROCEDURE

The first step in the procedure was to remove air from the system, including the injection water and the dry core, by vacuum pump evacuation to the maximum attainable vacuum under the existent atmospheric conditions. The core was then saturated with distilled water. In order to

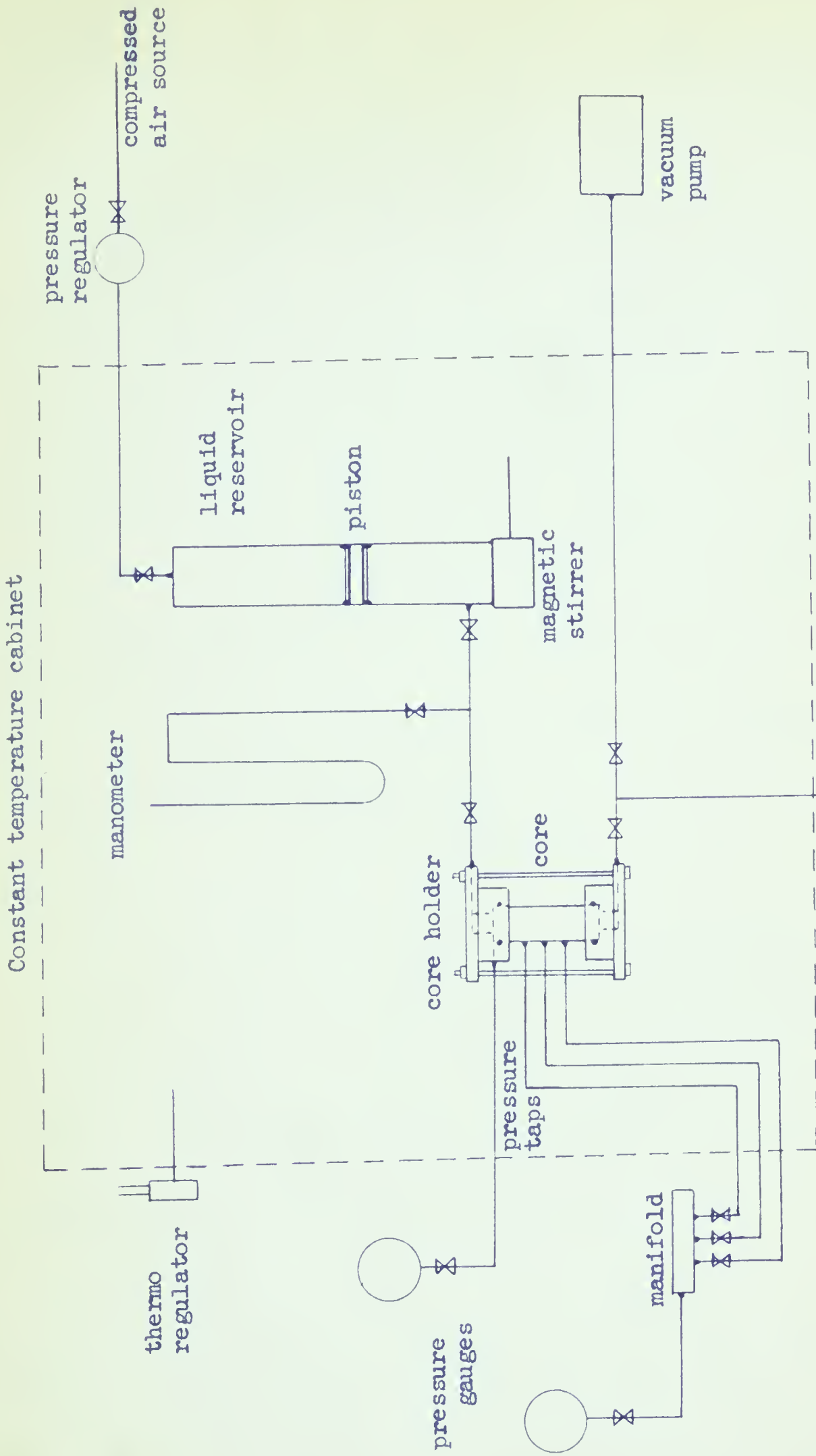


Figure 1. Schematic Diagram of Experimental Equipment

eliminate any swelling effect due to distilled water an initial test run was made to the point where neither a change in the individual pressure drops nor a change in flow rate occurred. The actual test began with the injection of air free water containing bacteria in a definite concentration. The pressure drops between taps and the corresponding flow rates were recorded at given time intervals. This process was continued until there was no change in permeability, indicated by constant flow rates and pressure readings. All tests were conducted in the pattern described above using different concentrations of bacteria in cores of various permeabilities.

The permeability of the core was calculated from the data obtained by the formula:

$$K = \frac{Q \mu L}{A \Delta P}$$

Where: K = permeability in darcys
Q = flow rate in c.c./sec.
P = pressure difference in atmospheres
L = length of core in centimeters
A = cross-sectional area of core in square centimeters
μ = viscosity in centipoises

The entire process was conducted at 100°F at which temperature the viscosity of water is 0.685 centipoises.

DISCUSSION OF EXPERIMENTAL PROCEDURE

During the initial runs an unusual phenomena was recognized which altered the character of pressure profiles by decreasing the permeability of the reservoir rock. Analysis of the pressure profile developed during initial runs showed that most of the pressure drop occurred at the outlet end of the core, contrary to what would be expected if plugging was taking place due to solid particles in the injected water. At the same time air was observed at the outlet end of the core. This evidence led to the hypothesis that air dissolved in the injection water under 40 psi was coming out of solution as the pressure dropped to atmospheric at the core outlet. Some of this air was coming out inside the core forming small bubbles and resulting in "gas blocking". Therefore it was necessary to eliminate the presence of air in order to provide accurate experimental measurements.

The injection water stored in the plastic reservoir proved to contain a certain amount of air in solution. As the pressure inside the core decreased, air escaped from the water in the form of bubbles which were trapped in the pores At first there was not a sufficient amount of air to create a critical air saturation. The air was in the immobile state preventing the movement of water. Gradually a critical saturation was reached and air began to move along the

channels. The larger the amount of air, the higher was the resistance of the porous media to the flow of the water phase. Eventually a time was reached when water practically ceased to flow. This effect is commonly referred to as the "capillary end effect."

Graphs of data from two of the early experimental runs have been chosen to demonstrate the misleading effects of air plugging in the evaluation of the results. The effect of air in distilled water is shown on Figure 2. The first curve indicates a constant pressure gradient throughout the core while subsequent curves indicate an increase in pressure gradients at the outlet end of the core which becomes more severe with time. This increased pressure gradient represents the reduction in permeability due to the presence of free air in the core. The combined effect of bacteria and air is illustrated in Figure 3. The initial pressure profile is similar to that obtained with distilled water shown in Figure 2, but subsequent profiles show an increasing pressure drop at both ends of the core. Early in the run the plugging effect of bacteria tends to be dominant at the input end of the core (curves 2 and 3). Later in the run (curves 4 and 5) the pressure profiles indicate the plugging to be dominant at the core outlet. The determination of the plugging effect of bacteria would have been very difficult, if not impossible,

Curve No.	Time (hrs)	Permeability (mds)	K/Ki (%)
1	Initial	64.2	100.0
2	19	46.7	72.8
3	24	36.5	56.9
4	47	21.9	34.1

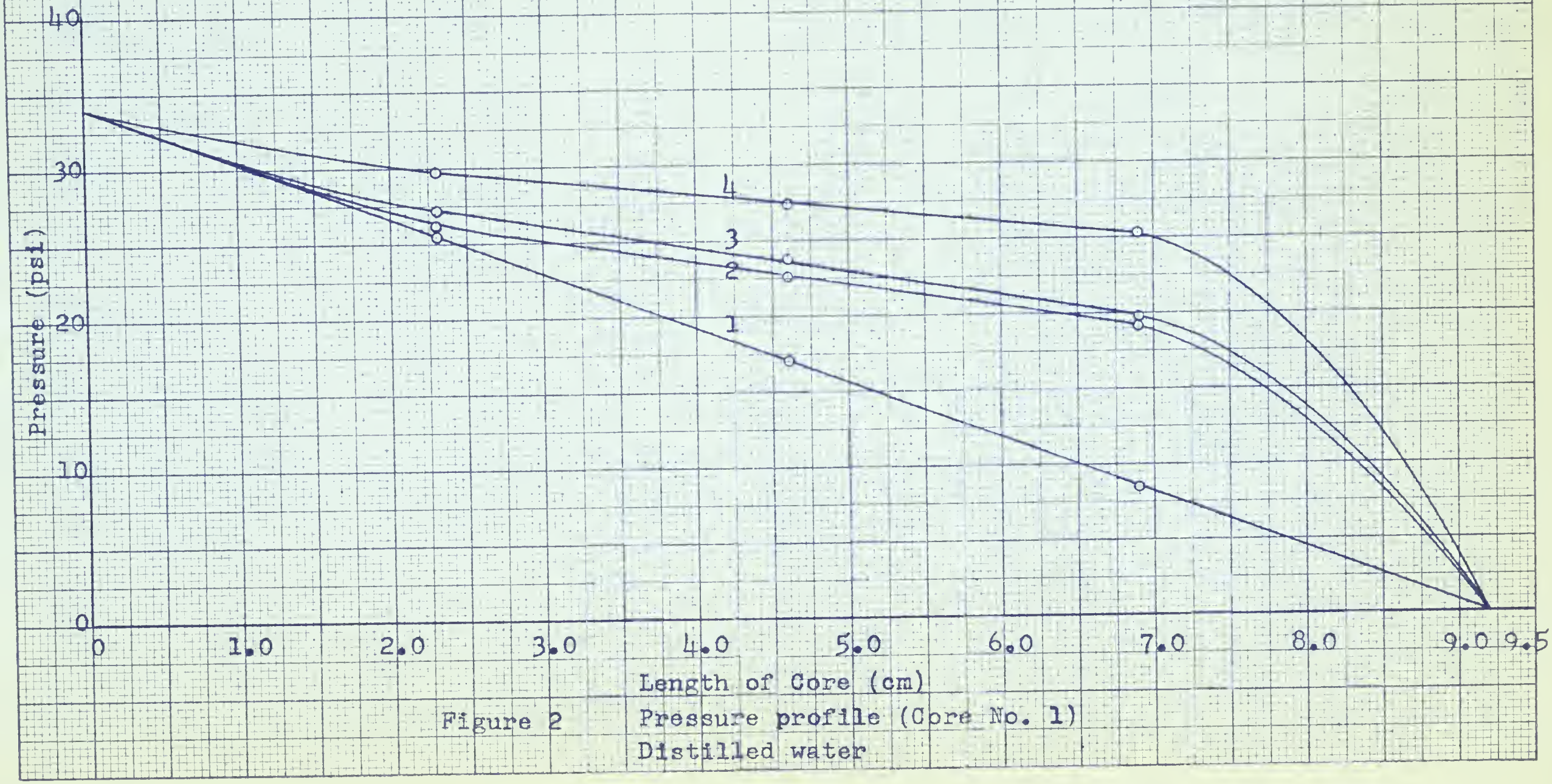


Figure 2 Pressure profile (Core No. 1)
Distilled water

Curve No.	Time (hrs)	Permeability (mds)	K/Ki (%)
1	Initial	68.2	100.0
2	2	58.9	86.4
3	3	41.7	61.1
4	5	15.9	23.4
5	9	5.6	8.2

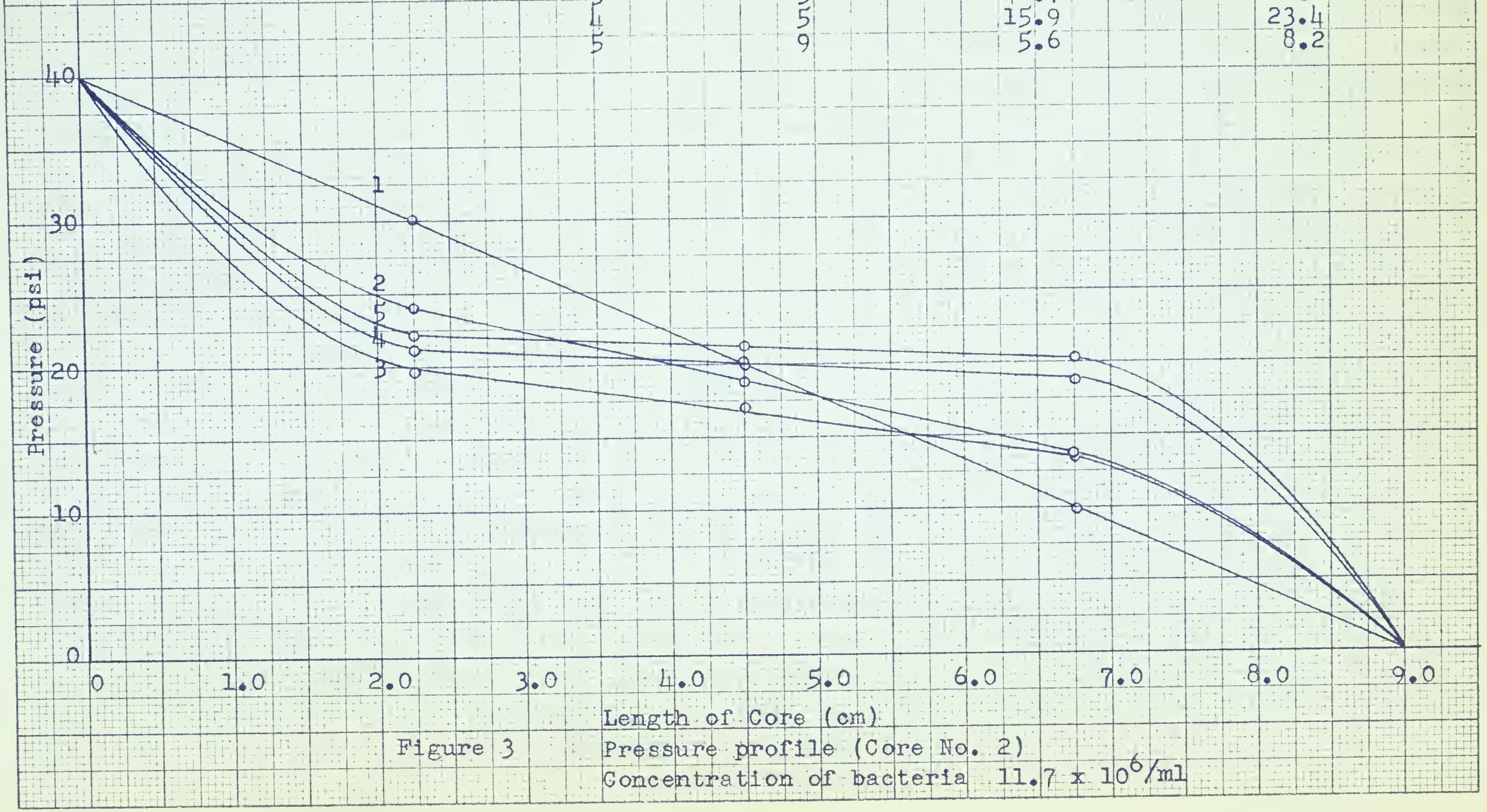


Figure 3 Pressure profile (Core No. 2)
Concentration of bacteria 11.7 x 10^6/ml

under these conditions, therefore it was necessary to eliminate air from the system entirely. Several techniques were attempted for establishing and maintaining an air free system before complete success occurred. The highlights of these attempts are mentioned herein since they are considered important laboratory technique developments.

In the early experimental runs air was removed only from the core, but in filling the storage cylinder with water air was mixed with the water and upon the increased pressure due to the hydrostatic head this air was dissolved in the water. This problem was solved by evacuating air from the cylinder after it was filled with injection water.

However, another air source still existed since during the injection. air was used as the driving medium in direct contact with the water. Placing a barrier between the air and water was obviously suggested to prevent air from re-dissolving in the water, but the development of an adequate barrier technique turned out to be a time consuming problem.

The first attempt to provide a barrier utilized a custom-made rubber inner tube between the air and water. Upon subjection to pressure and temperature these socks developed leaks along vulcanized areas. The next step was to adapt a weather balloon in a similar fashion. These balloons having large surface areas, became complexly folded in the cylinder trapping considerable amounts of air which could not be removed by evacuation.

The final attempt and successful solution to the problem was to install a free running piston equipped with leather cups to act as the barrier between the air and water. Establishing and maintaining an air free system was accomplished as follows. A reservoir containing the air free water was connected to the outlet end of the evacuated source cylinder. At this time the free running piston was sealed at the lower end of the cylinder. A vacuum was produced at the upper end causing the piston to move upward drawing the water into the cylinder. During the runs compressed air pressure was applied on the upper side of the piston which by moving downward injected water into the core. The leather cups and O-rings mounted on the piston made adequate contact with the wall of the cylinder to prevent air by-passing.

DISCUSSION OF RESULTS

During the experimental work actual measurements were made on 30 core samples, but due to initial difficulties in the equipment, data from some of these were useless. The results of twelve cores, considered to be the most accurate and representative, were selected to illustrate the plugging effect of bacteria cells. In order to obtain conclusive results it was necessary to separate the variables and analyze the effect of each one individually.

All runs except one were made at a 40 psi pressure differential. Input pressure was maintained constant throughout the runs. As the total volume of water injected increased flow rates through the cores decreased as resistance to flow increased due to plugging.

The reduction in total core permeability from initial distilled water permeability has been used as a measure of the degree of bacteria plugging. Plugging was analysed using plots of the ratio of reduced (plugged) permeabilities to initial permeability versus input water volume, using both absolute initial core permeability and bacteria concentration as parameters. The penetration depth of the plugging bacteria cells was studied from the plots of flowing pressure (at the various pressure taps) versus length of core. These pressure profiles were prepared with time as the parameter.

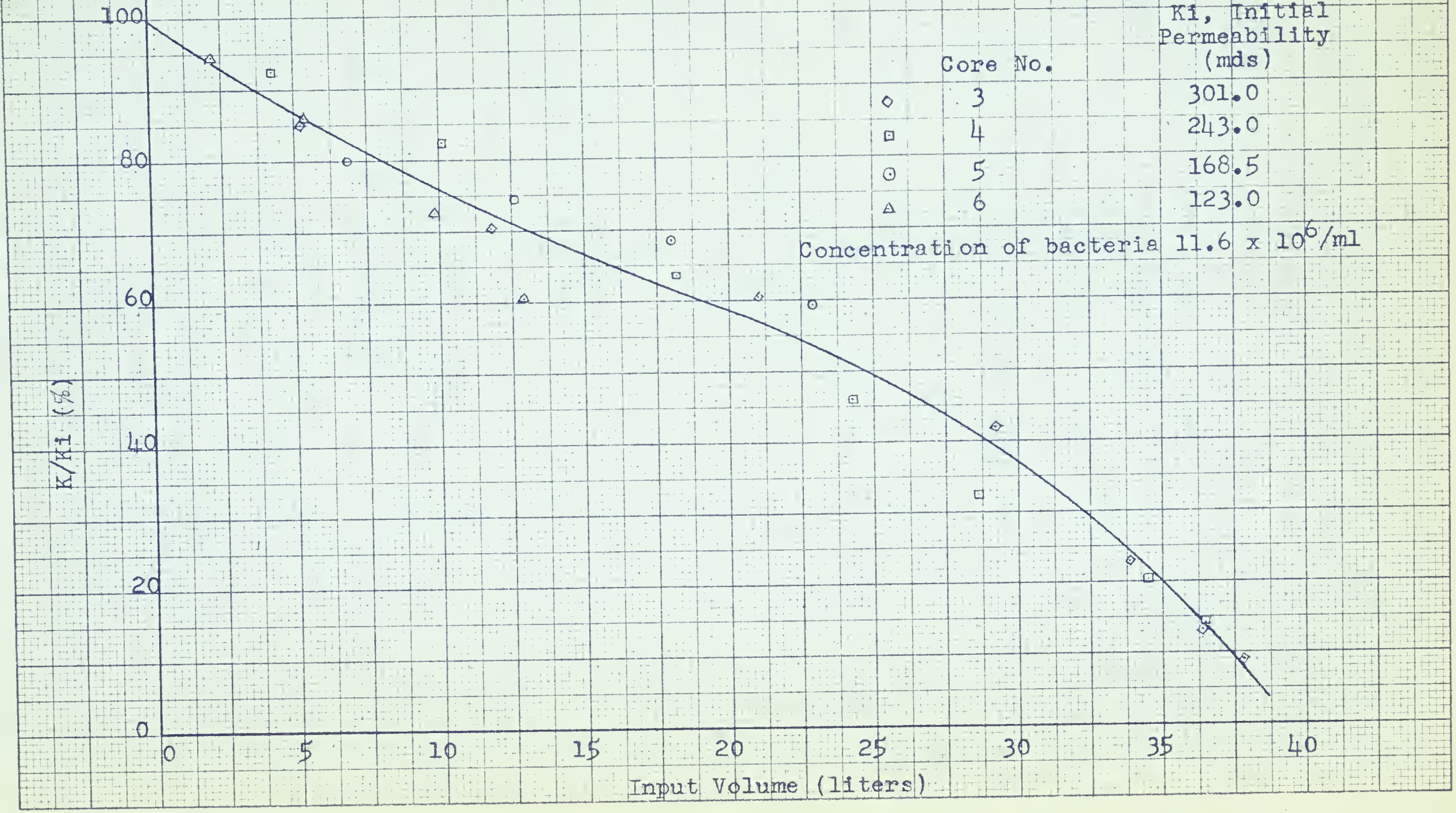
PERMEABILITY

The effect of permeability on the plugging of bacteria is illustrated by four cores of permeabilities between 123 and 301 millidarcies. Figure 4 shows the plugging of these cores with a bacteria concentration of 1.16×10^6/ml. Scattering of the points from various cores precluded drawing a series of curves for permeability variation. However, a significant trend in the data obtained was apparent and the results from runs for all permeabilities were plotted into a composite curve. Since it was impossible to distinguish any significant difference in plugging in cores of different permeabilities, it appears that the extent of plugging is independent on the permeability. The reason for this behavior probably lies in the fact that all cores were taken from the same formation and have a similar textural structure. Since the mechanism of particle plugging is by bridging the pore cross-section with the plugging particles, the plugging effect of bacteria is influenced by the pore size and shape. Variations in permeability may have been due to variations in cementation of the sand system, but this cementation did not appreciably affect pore size and, therefore had little effect on the bridging mechanism.

Analyzing the shape of the curve it is seen that at the beginning of water injection plugging occurred at a greater

Figure 4 Permeability Ratio vs Input Volume

For Cores of Various Ki's at Constant Bacteria Concentration



	Core No.	Ki, Initial Permeability (mds)
◇	3	301.0
⊡	4	243.0
⊙	5	168.5
△	6	123.0

Concentration of bacteria 11.6×10^6/ml

rate, as shown by the steep decrease in permeability. This was due to the fact that the small pores of the core were plugged rapidly. The middle section of the curve shows a smaller slope, during which period bacteria cells accumulated in channels of large size and plugged channels of moderate size. When the accumulation of bacteria cells was sufficient to plug even the large channels the flow of injection water practically ceased as the core permeability declined rapidly, as shown by the last part of the curve.

CONCENTRATION OF BACTERIA

Figures 5, 6 and 7 show the important role of the concentration of bacteria cells in distilled water on plugging the formation. Figure 5 shows permeabilities of nearly the same initial values plotted against input volume using bacteria concentrations of 11.6×10^6/ml, 1.16×10^6/ml and 0.116×10^6/ml. The characteristics of the curves are the same as previously noted, i.e., the three different sections are clearly distinguishable, but the concentration shows a great effect in reducing permeability. Increased concentration means a greater mass of bacteria in the same volume of input water and results in increased plugging of cores at any given input volume. This is indicated clearly by the position of the curves on the graph.

On Figure 6 concentration versus input volume

Figure 5 Permeability Ratio vs Input Volume For Cores with Similar Ki's at Various Bacteria Concentrations

	Core No.	Concentration of Bacteria
△	7	11.600×10^6/ml
◇	3	1.160×10^6/ml
○	8	0.116×10^6/ml

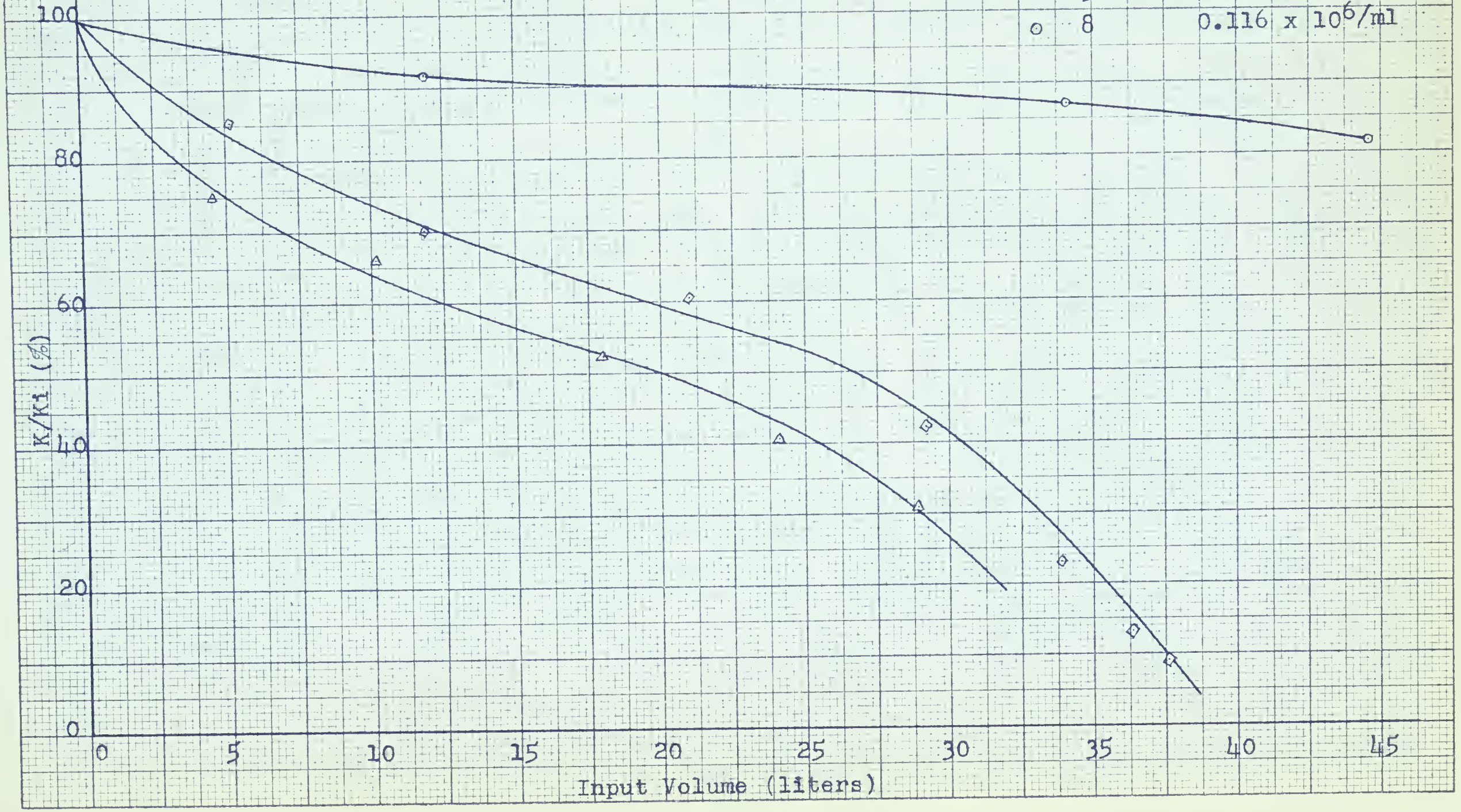


Figure 6

Concentration of Bacteria v.s. Input Volume

For Cores of Similar Initial Permeabilities

Curve No.	K/Ki (%)
1	95
2	90
3	85

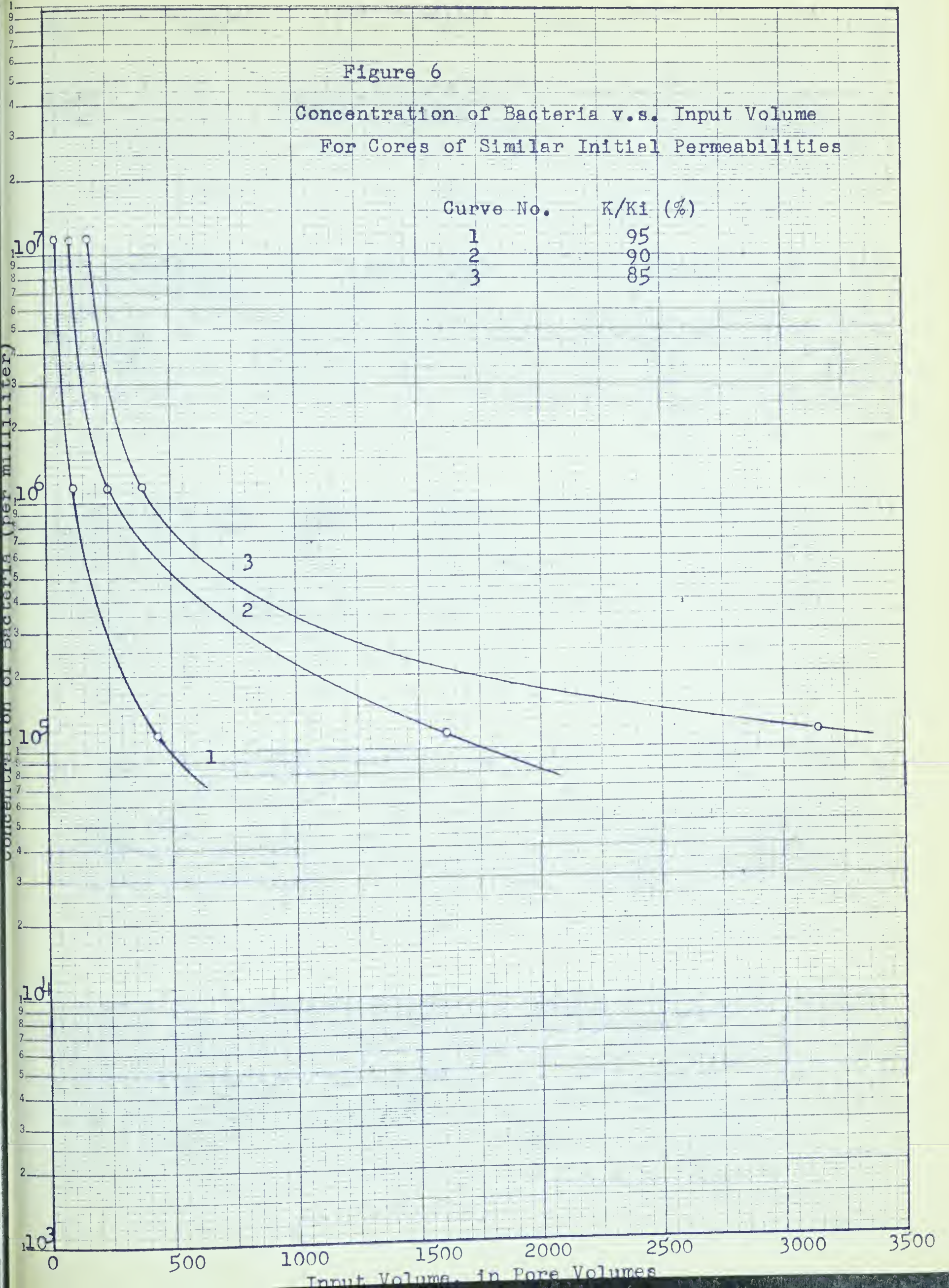
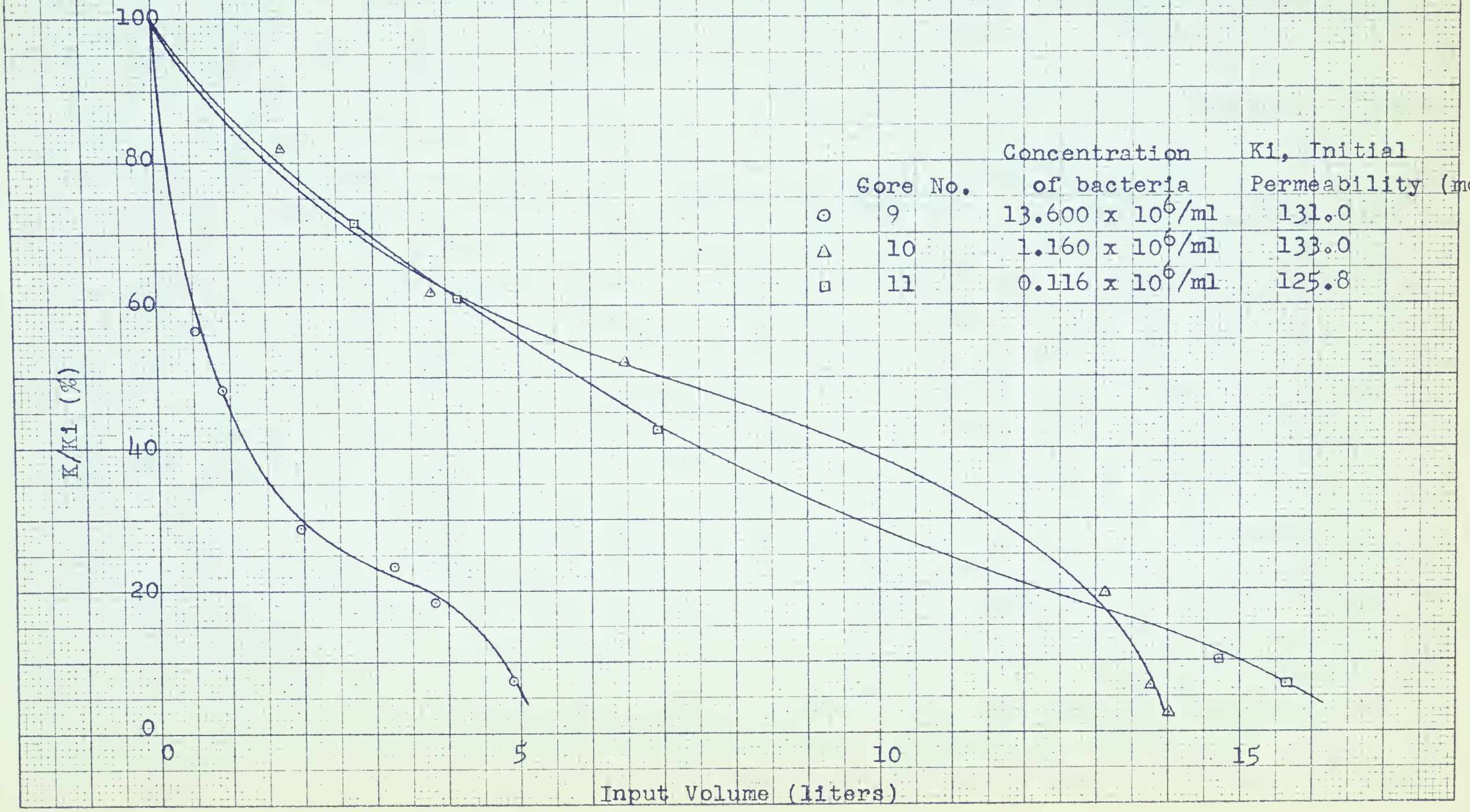


Figure 7 Permeability Ratio vs Input Volume

For Cores with Similar Ki's at Various Bacteria Concentrations



	Core No.	Concentration of bacteria	Ki, Initial Permeability (mds)
⊙	9	13.600 x 10^6/ml	131.0
△	10	1.160 x 10^6/ml	133.0
□	11	0.116 x 10^6/ml	125.8

input volume in pore volumes was plotted using the permeability ratio as a parameter. As the bacteria concentration was reduced the input to cause any given degree of plugging was increased. However, the absolute number of bacteria injected to these same points decreased.

Figure 7 represents the results obtained on cores of lower, but still essentially equal initial permeabilities with bacteria concentrations of 13.6×10^6/ml, 1.16×10^6/ml and 0.116×10^6/ml. Comparing this curve to that of Figure 5 a certain discrepancy is observed. Although the core samples were taken from the same formation some samples contained clay resulting in a significant swelling effect which showed particularly in the cores represented on Figure 7. It was impractical to eliminate the swelling effect during initial distilled water runs, and this phenomena continued to show its effect during the actual run with bacteria. Although the data shown on these curves are inconclusive as to the relation of concentration to plugging, the general characteristics of the curves are again similar to those of other experimental runs. In the case of the run using a high bacteria concentration, unexpected rapid plugging occurred which was probably due to the extremely high swelling of clay. Considerably smaller swelling was observed on the core with medium bacteria concentration, yet comparing this to the same

curve of Figure 5 a significant deviation may be noted. The results obtained for the low concentration would be expected to fall on a line showing a smaller plugging rate than that of the two previous cores, but due to the high swelling effect the curve followed the line representing the case of medium concentration. Further implications of clay swelling are discussed in the next section

CORE PARTICLE AND CLAY SWELLING PLUGGING

The changes in permeability throughout the cores can be analyzed by means of pressure profiles. Two outside factors which altered the character of the pressure profiles must be briefly discussed.

Pressures obtained at the pressure taps for each core were plotted as pressure profiles for different concentrations of bacteria using time as the parameter. During the initial runs with distilled water containing no bacteria the pressure gradient was greater in the first section of the core indicating a certain amount of plugging. One explanation of this phenomena may be that when cutting the cores, small rock particles were left in the pores that were impossible to remove by brushing or air blowing. Upon injecting through the core these particles moved and caused plugging near the input sand face. Figures 8, 9 and 10 illustrate this phenomena. Curve No. 2 of each figure shows a large pressure gradient in the first section of the core and a uniform smaller gradient in the remainder of the core.

Curve No.	Time (hrs)	Permeability (mds)
1	Initial	131.0
2	Start of test	78.4
3	1	44.8
4	2	38.0
5	6	23.4
6	13	18.6
7	17	14.8
8	31	6.1

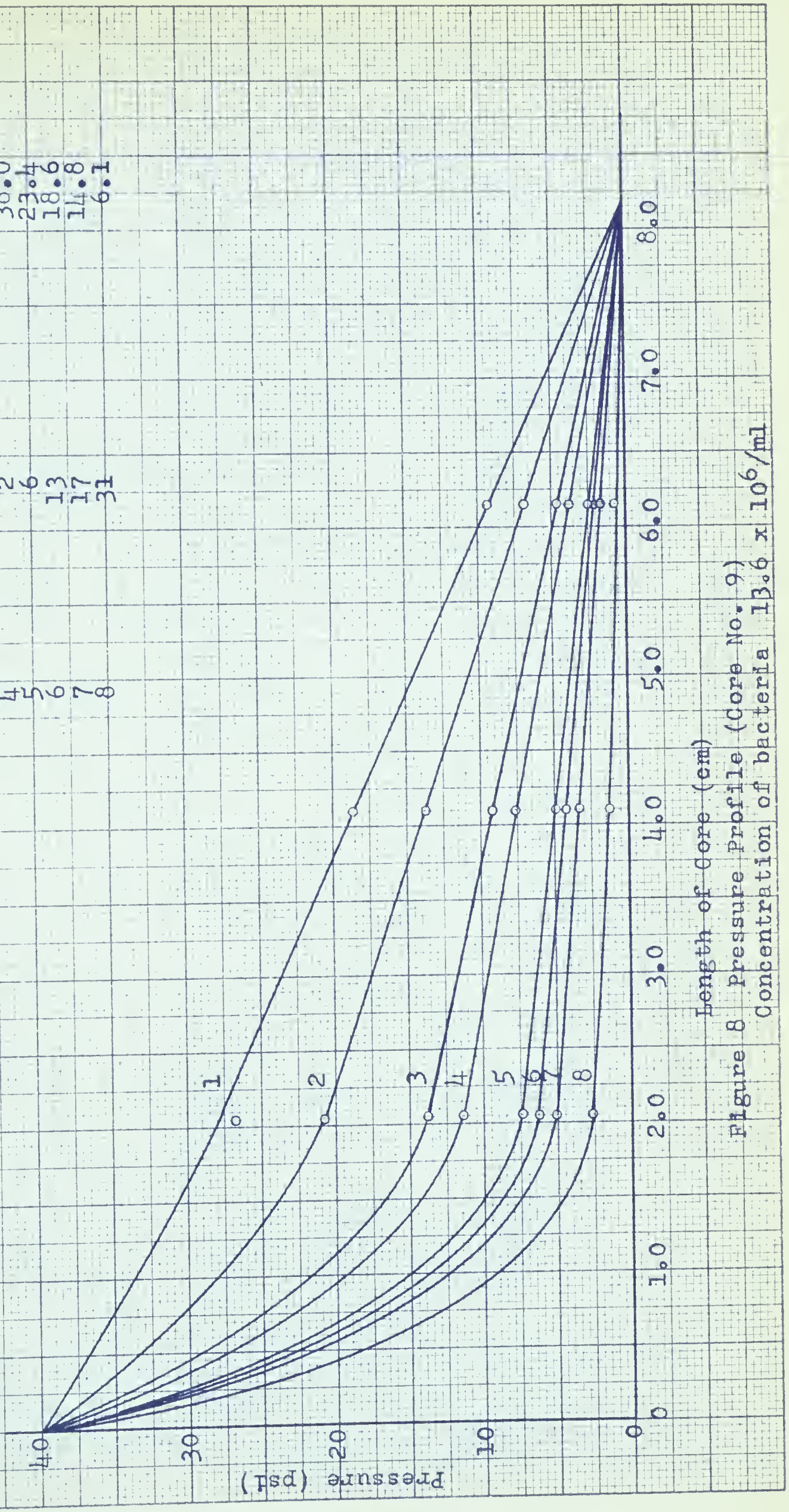


Figure 8 Pressure profile (Core No. 9)
Concentration of bacteria 13.6 x 10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial	133.4
2	Start of Test	119.8
3	2	97.3
4	5	73.8
5	10	59.9
6	30	23.2
7	35	7.9
8	40	3.4

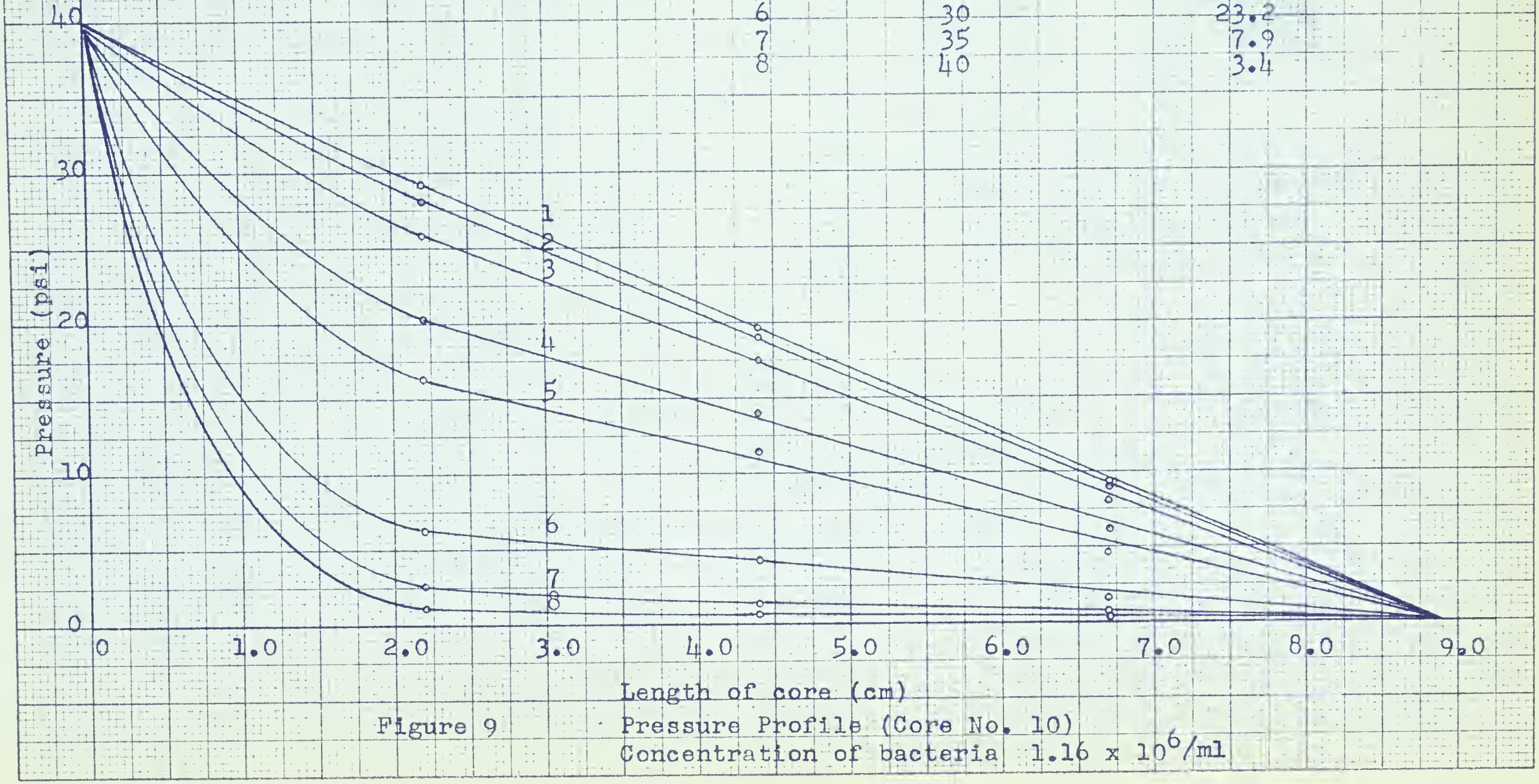


Figure 9 Pressure Profile (Core No. 10)
Concentration of bacteria 1.16×10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial	125.8
2	Start of Test	117.5
3	3	83.9
4	5	71.6
5	10	50.3
6	17	36.3
7	40	11.9
8	50	9.9

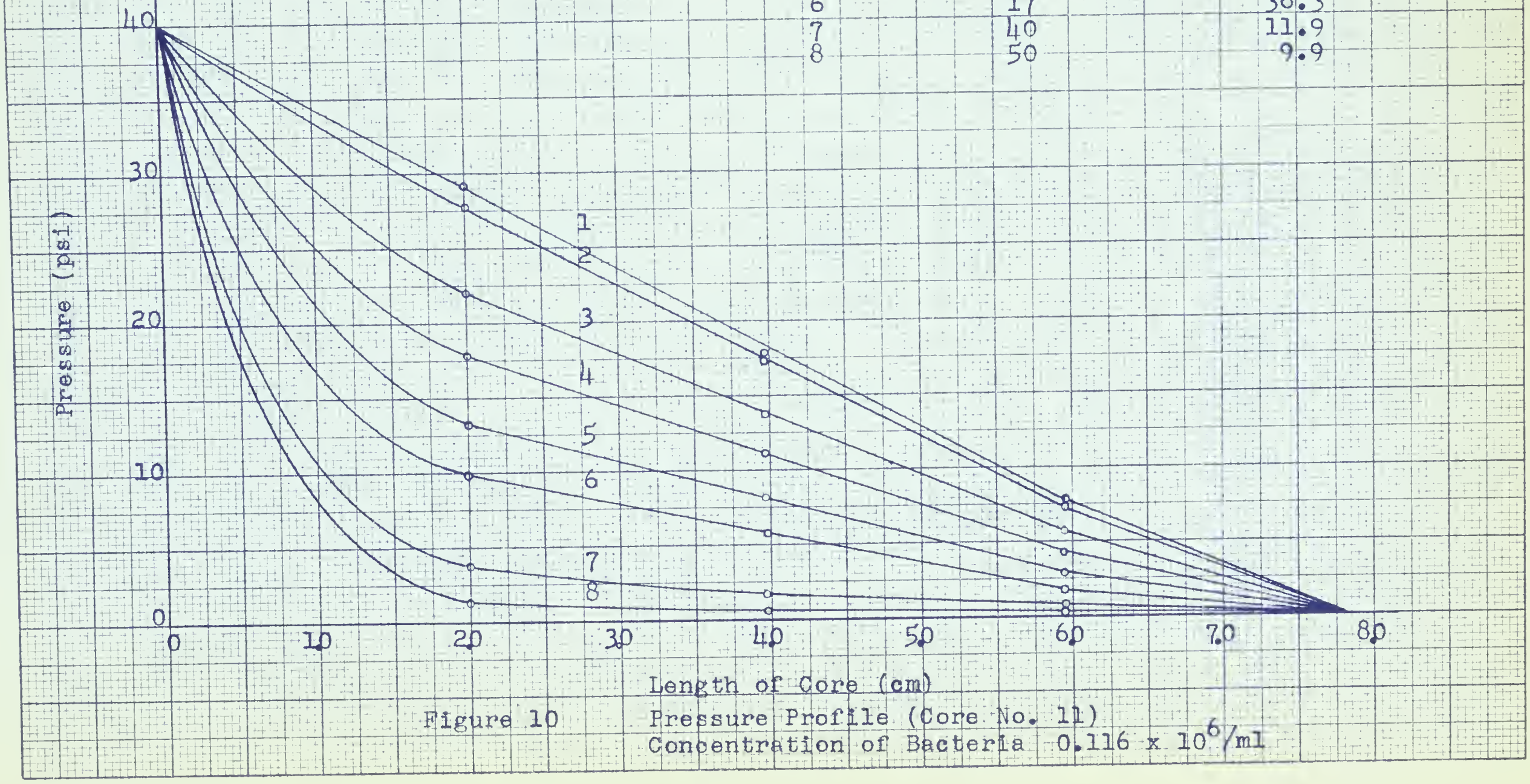


Figure 10 Pressure Profile (Core No. 11)
Concentration of Bacteria 0.116 x 10^6/ml

The pressure profile curves do not show plugging due to clay swelling. However, this phenomena was quite pronounced in some cores shown by reductions in flow rates as distilled water was injected at constant input pressure. Data supporting this fact appear in Table X, XI and XII.

PENETRATION DEPTH

The analysis of penetration depth of bacteria cells can be made in several ways: 1, Taking water samples at the pressure taps and at the outflow and counting the number of bacteria cells present, or 2, Using the shape of the pressure profile obtained along the core using time as the parameter.

Counting of dead bacteria cells would have been very difficult, so the Viable count method was applied to the living bacteria. However the equipment and the technique of the test were not sterile and the growth environment was not adequate for bacteria, therefore the results obtained by counting bacteria were not conclusive. However, some living bacteria were found in the outflow water which indicated a penetration depth of at least seven centimeters.

Since the counting technique was inadequate for penetration depth analysis, the pressure profile technique was used. Figures 8, 9 and 10 show the pressure profiles of cores contaminated with clay. Because of the swelling effect (i.e., reduction in pore size) great numbers of the bacteria

cells were deposited in the first section of the cores due to the reduced pore size, as shown by the high pressure gradients. Therefore, these cores showed more rapid plugging in comparison with cores of less clay content at the same concentration. As the runs proceeded in time greater lengths of core were penetrated by bacteria cells causing larger pressure gradients in the second sections of the cores than in the third and fourth sections. This is shown by curve No. 8 on Figure 8, Curve No. 7 on Figure 9 and on Figure 10. The ratio of reduced permeabilities to the initial permeability were plotted versus length of core for core No. 9 in Figure 11. The plugging of bacteria cells augmented by swelling is well illustrated. Only curve No. 7 shows the penetration of bacteria cells deeper then 2.05 centimeters (first pressure tap) into the core. The gradual reduction of permeability which occurred in the other parts of the core was merely the result of clay swelling.

Figures 12 - 18 represent the results obtained for uncontaminated cores where most of the plugging occurred also at the front part, but the bacteria cells moved farther into the core immediately after water injection started as indicated by non-uniform pressure gradients.

Runs made with higher concentrations of bacteria cells gave more effective plugging in the first section of the core. The reason for this is that the greater mass

Time (hrs)	
1	0
2	1
3	2
4	6
5	13
6	17
7	31

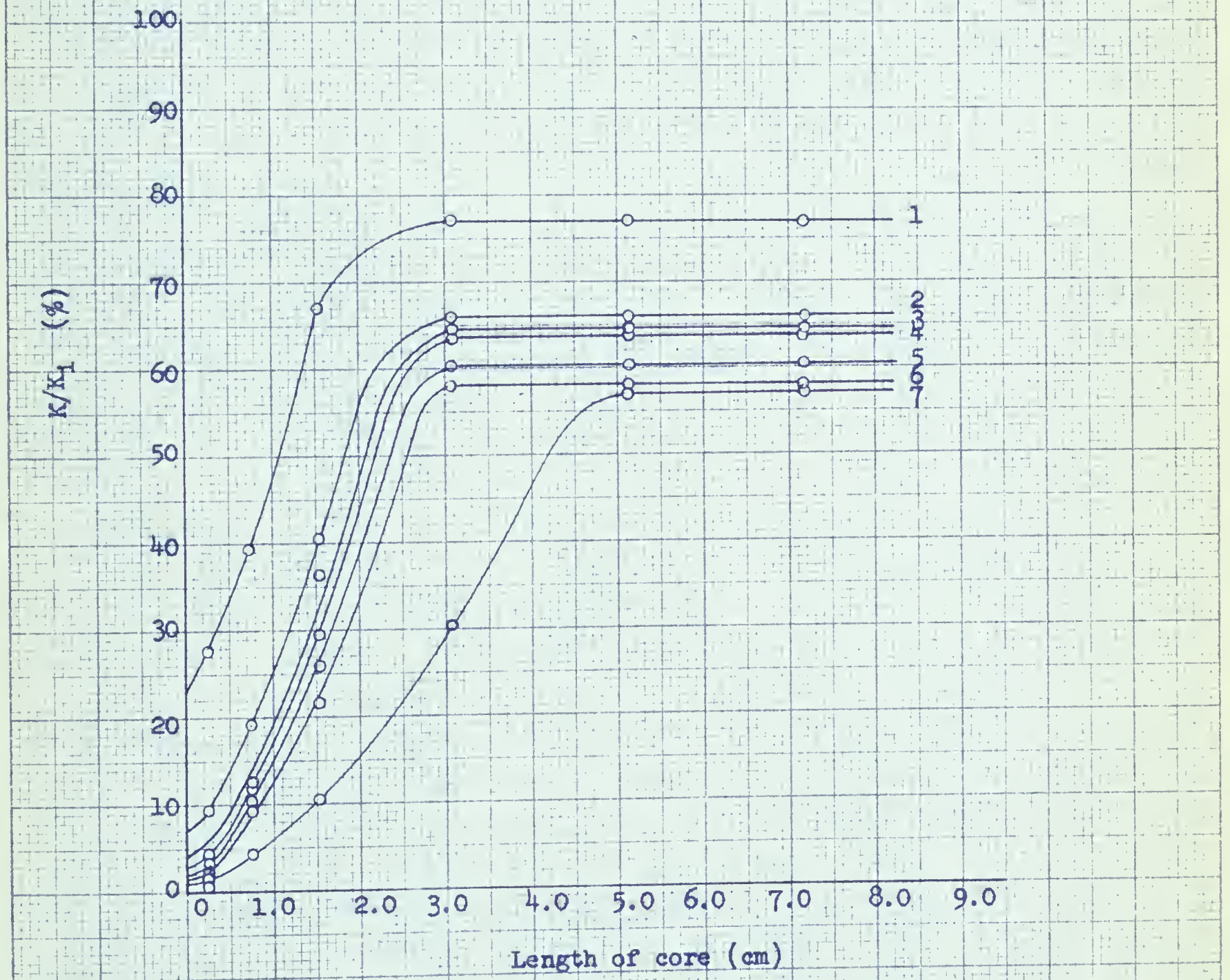


Figure 11. Permeability Ratio Profile (Core No. 9)
Concentration of bacteria: 13.6×10^6/ml.

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of Test	301.0
2	2	256.4
3	5	211.4
4	10	181.2
5	15	126.8
6	20	69.1
7	25	39.7
8	30	26.9

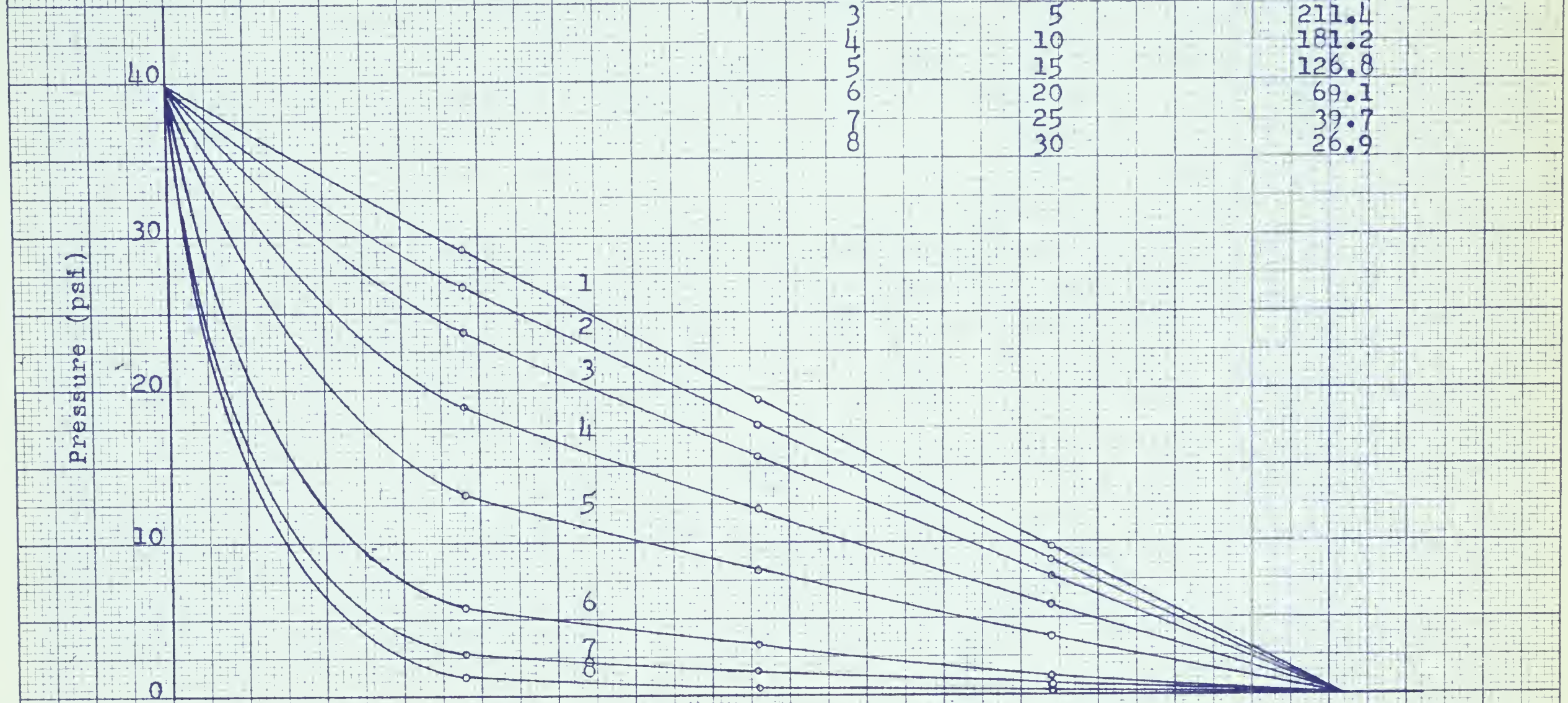


Figure 12 Pressure Profile (Core No. 3)
Concentration of Bacteria 1.16×10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of test	243.0
2	2	200.4
3	5	154.5
4	10	111.7
5	15	78.8
6	20	49.2
7	35	34.2

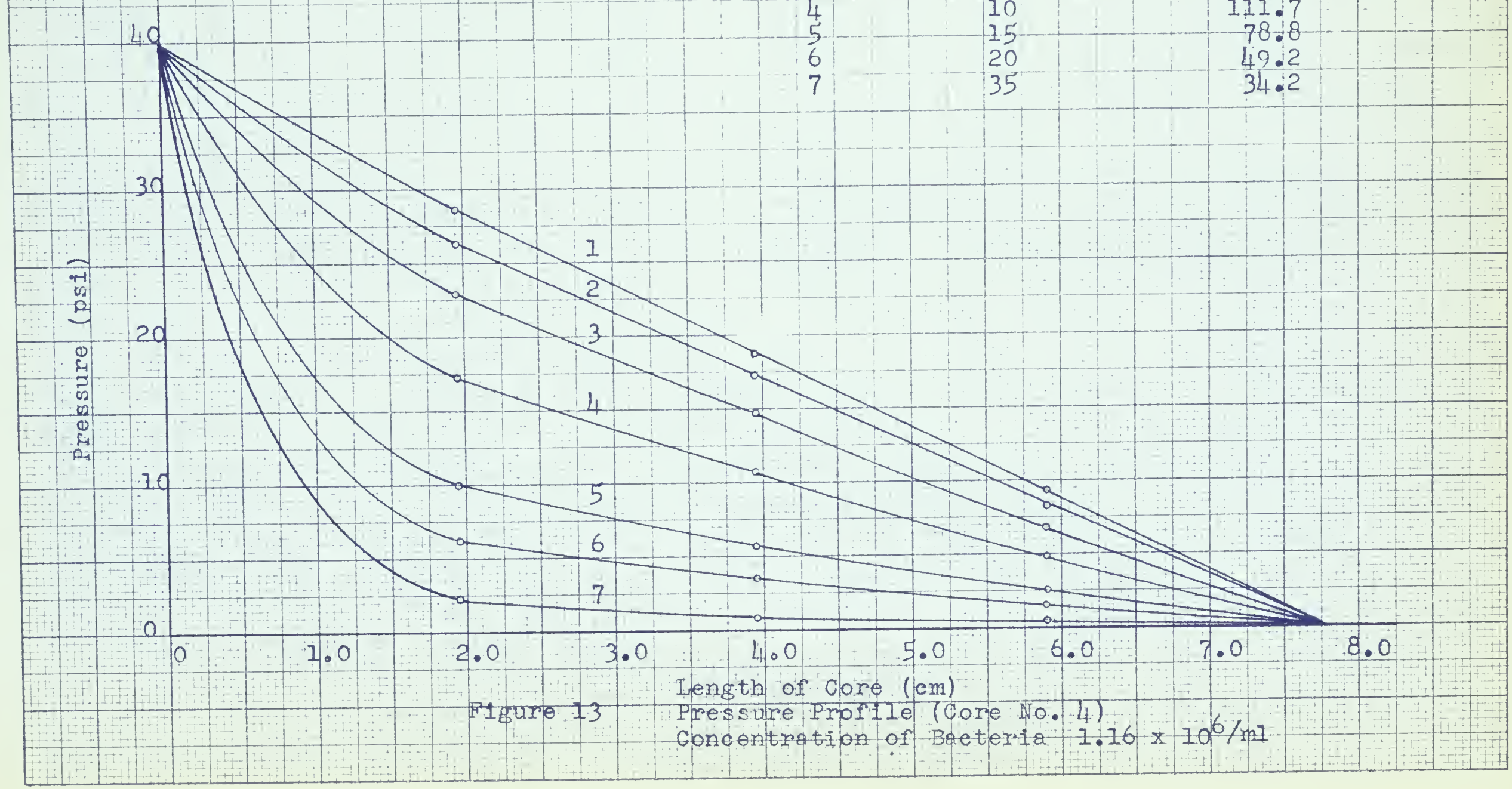


Figure 13 Pressure Profile (Core No. 4)
Concentration of Bacteria 1.16 x 10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of test	168.5
2	5	134.9
3	10	125.6
4	15	115.2
5	20	100.2

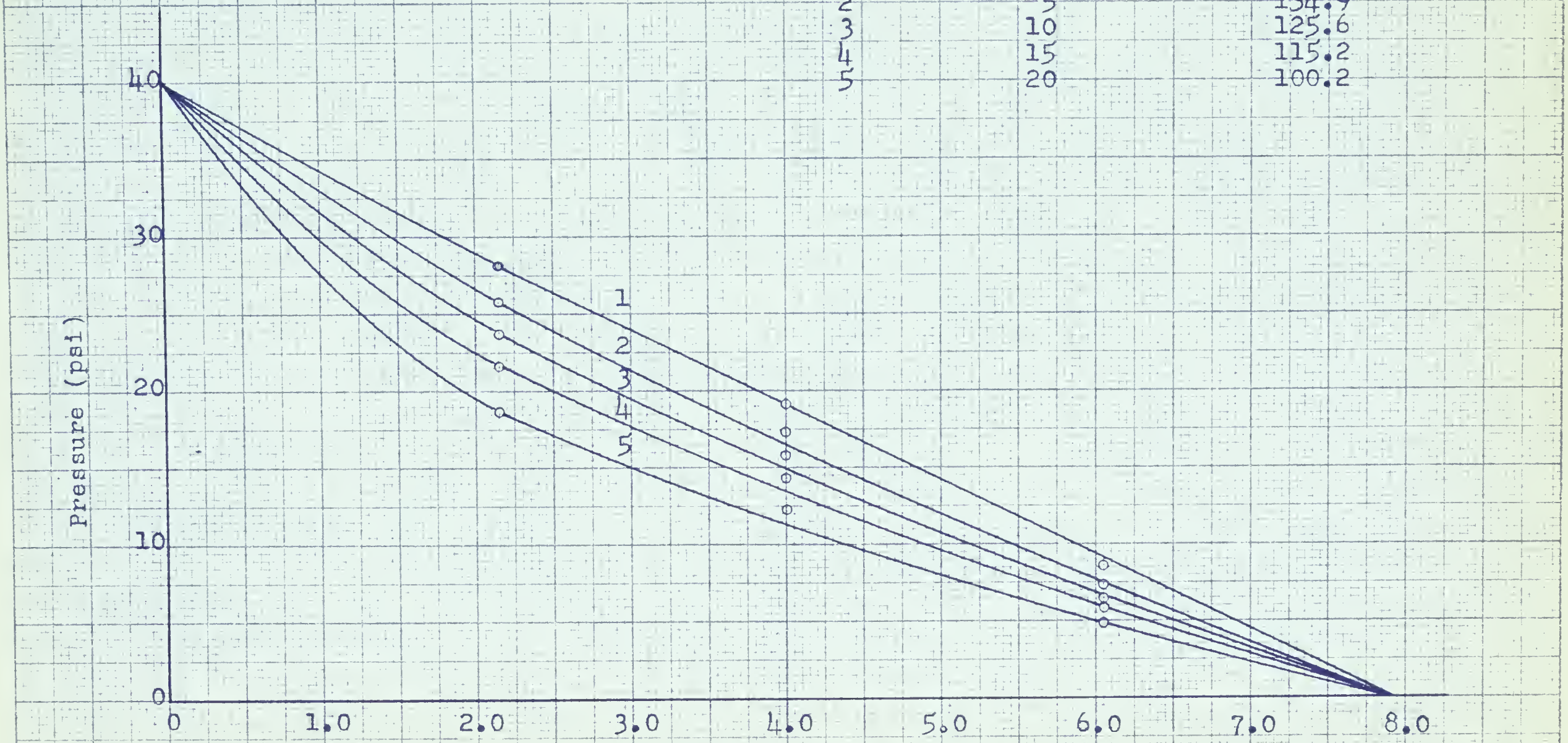


Figure 14

Pressure Profile (Core No. 5)
Concentration of Bacteria 1.16×10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of test	123.0
2	2	116.6
3	5	105.5
4	10	89.4
5	14	74.5

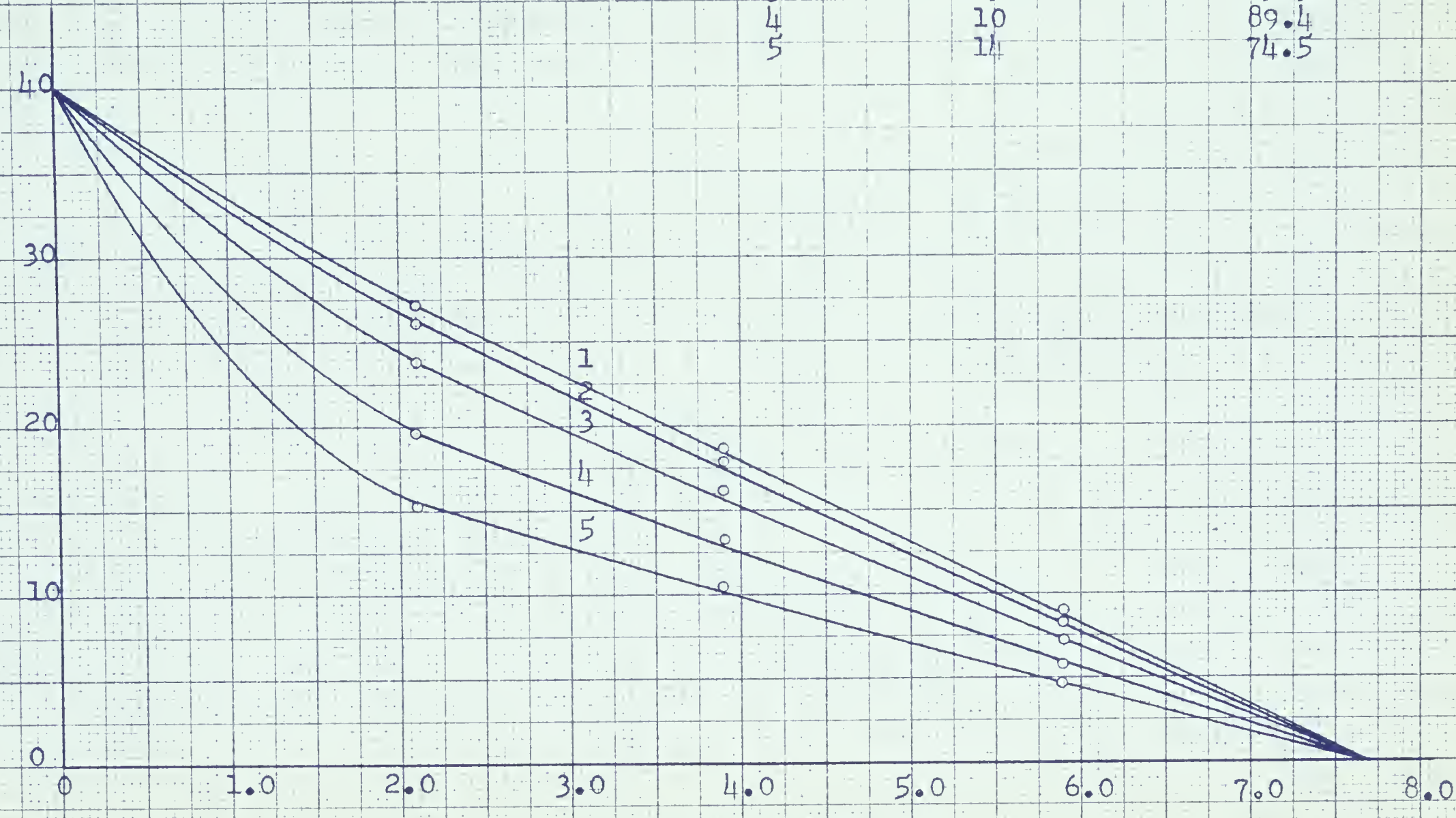


Figure 15

Pressure Profile (Core No. 6)
Concentration of Bacteria 1.16 x 10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of Test	285.0
2	2	213.6
3	5	188.0
4	10	149.2
5	15	116.6
6	20	88.0

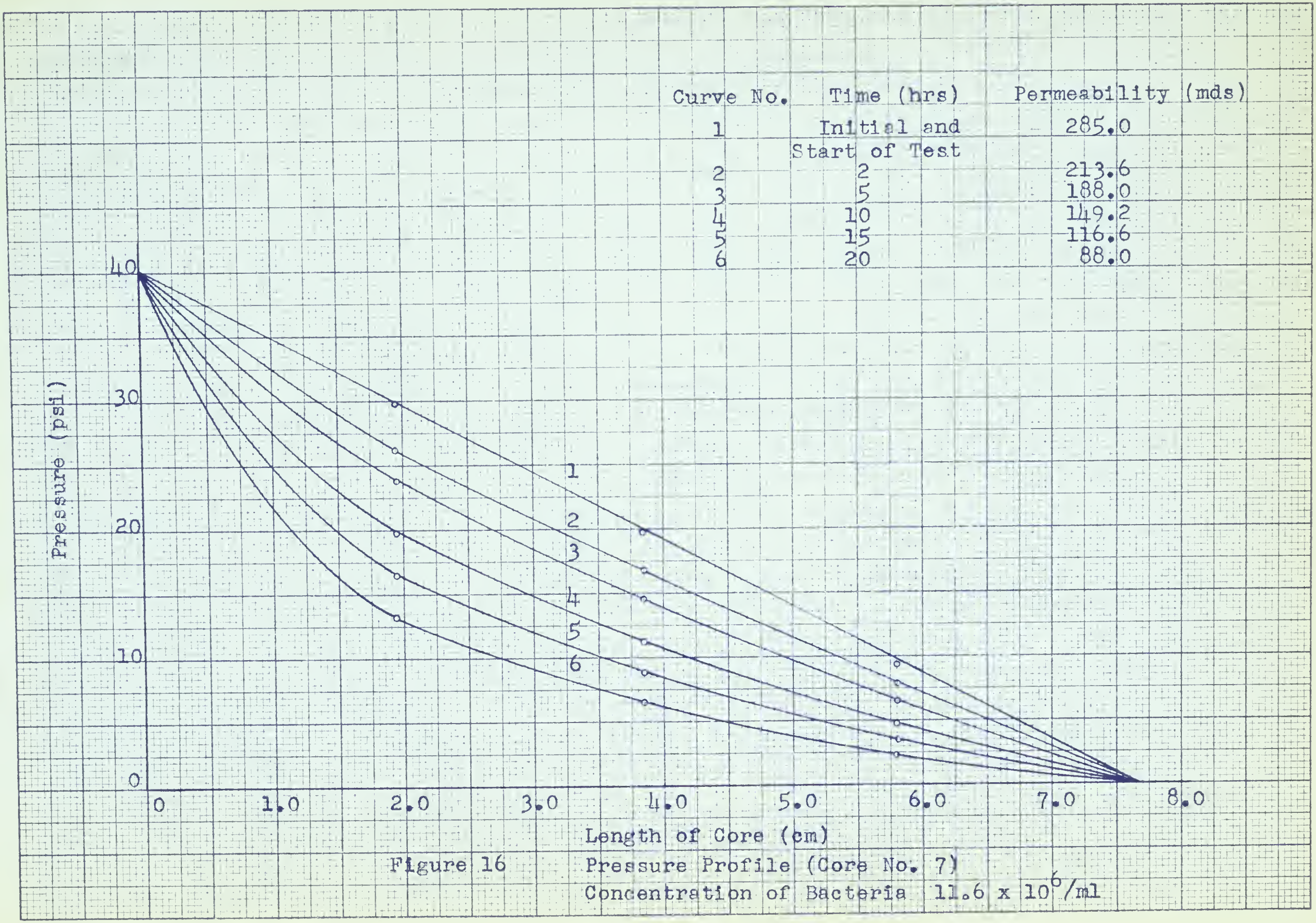


Figure 16 Pressure Profile (Core No. 7)
Concentration of Bacteria 11.6 x 10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of Test	282.0
2	5	255.0
3	15	245.5
4	20	229.5

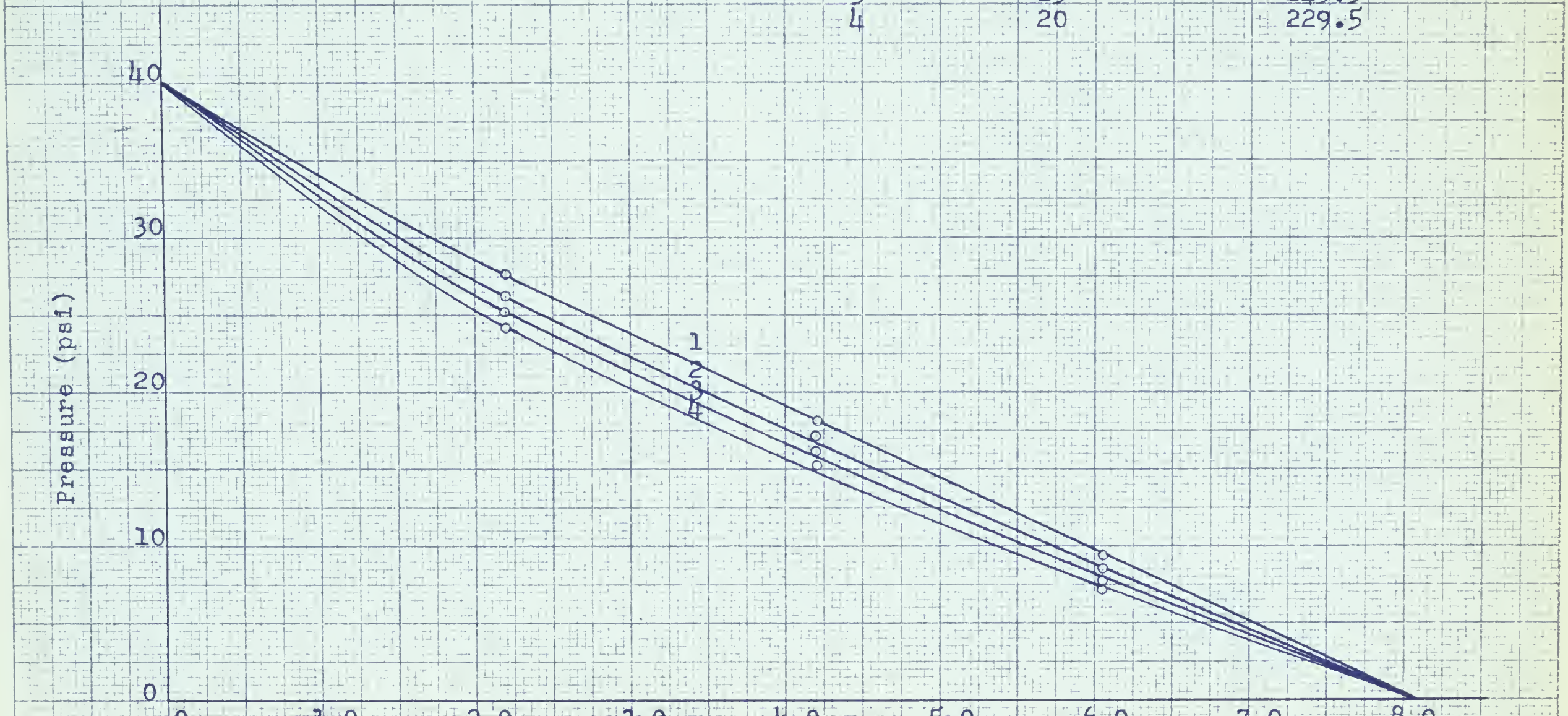


Figure 17 Pressure Profile (Core No. 8)
Concentration of Bacteria 0.116 x 10^6/ml

Curve No.	Time (hrs)	Permeability (mds)
1	Initial and Start of Test	181.0
2	2	159.0
3	5	144.6
4	10	125.1
5	15	108.8

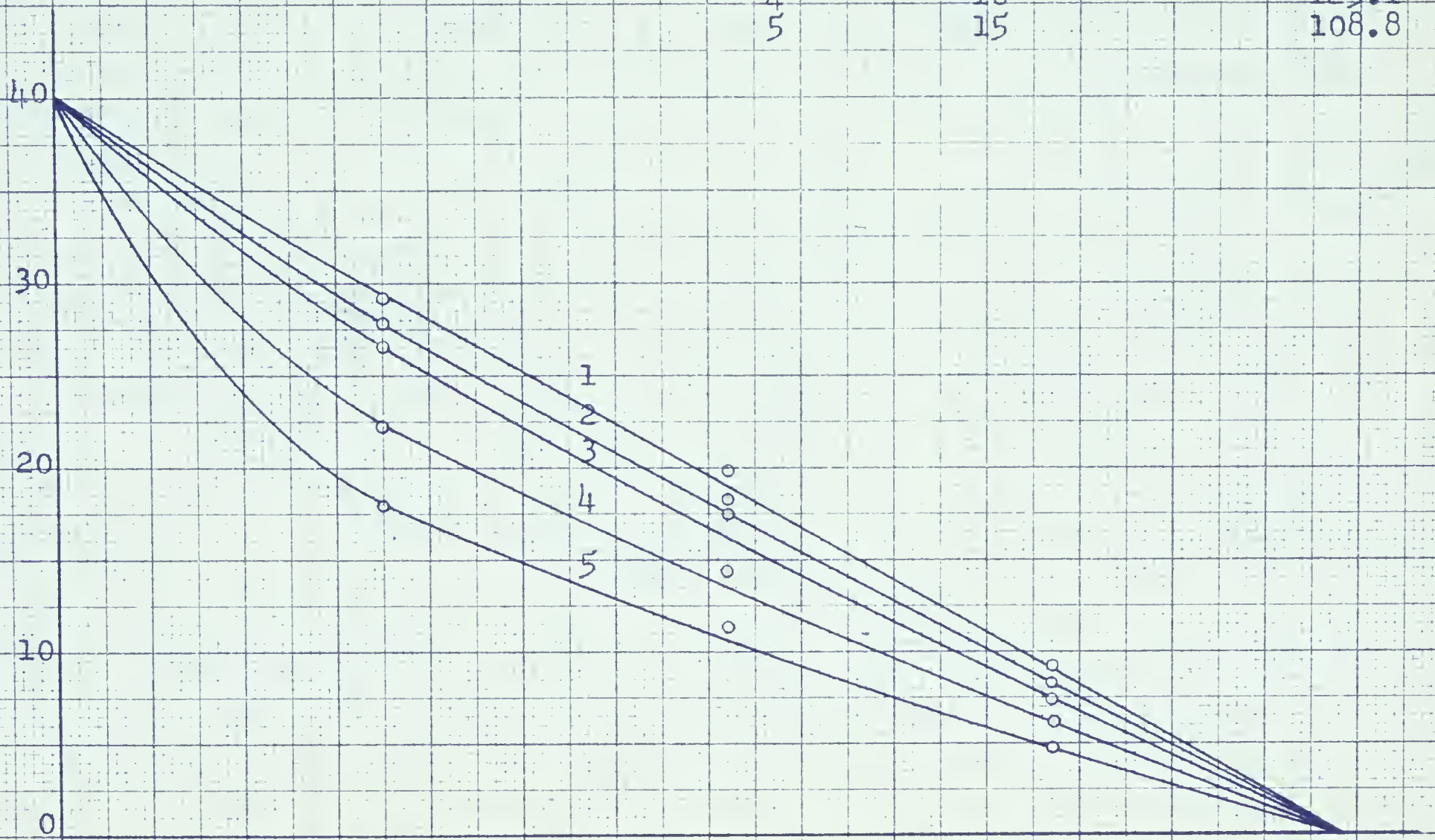


Figure 18 Pressure Profile (Core No. 12)
Concentration of Living Bacteria 1.16 x 10^6/ml

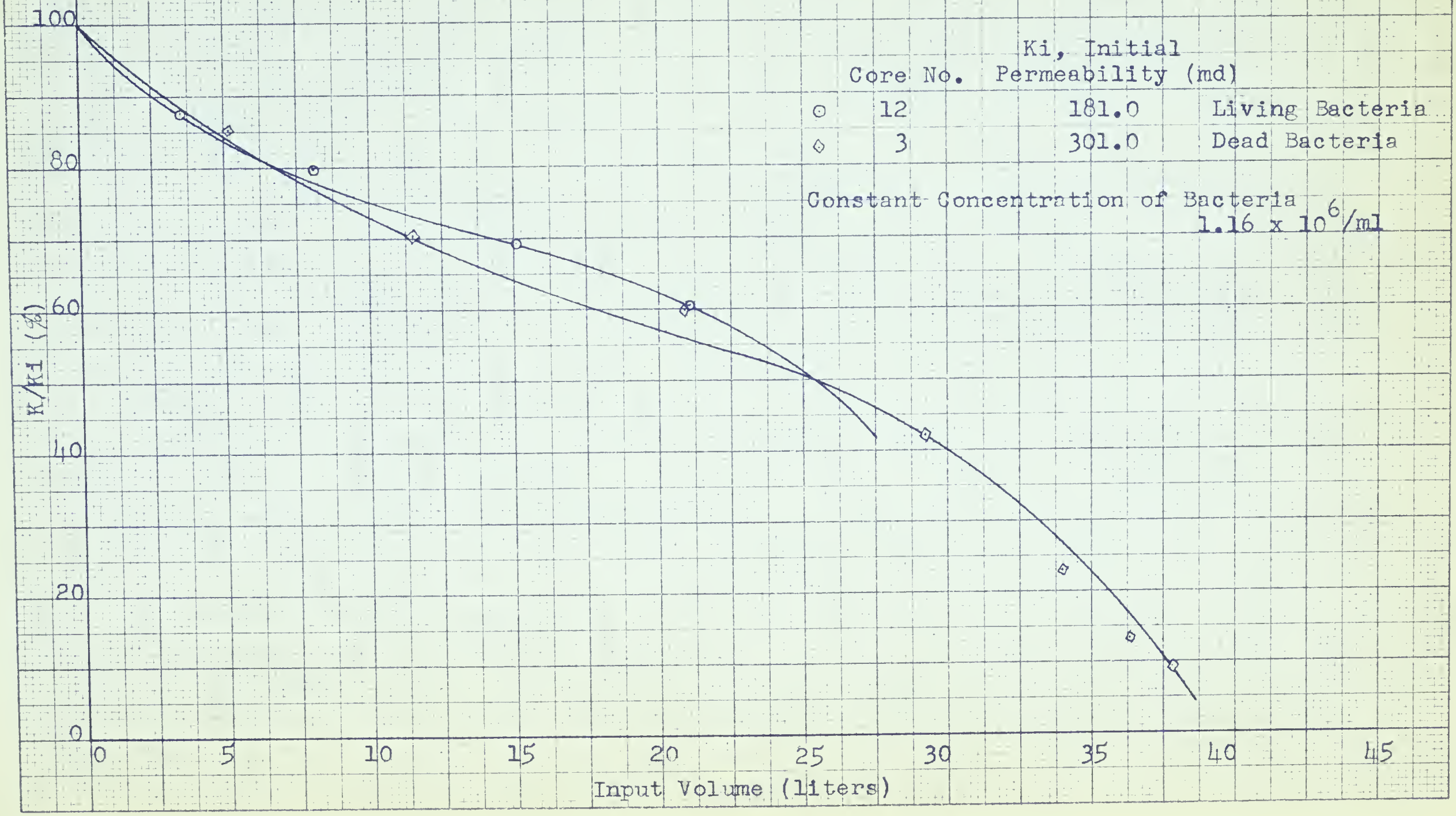
of bacteria cells per milliliter of injected water was able to plug the channels more rapidly and to such a degree that no more bacteria could pass. While in the case of low concentrations the process of plugging was comparatively slower creating more favorable conditions for the penetration of bacteria cells deeper into the core.

In summary, both pressure profile curves and bacteria counts indicate that some bacteria penetrated the entire core.

LIVE BACTERIA

Because of reasons discussed previously this study was conducted using dead bacteria cells, but in order to dissipate any doubt about the validity of the experimental work a run was made with living bacteria. For this purpose a core with permeability of 181 mds. was chosen using a 1.16×10^6/ml concentration of bacteria. Results of this run together with the results of core No. 3, which was a run with the same concentration but using dead bacteria cells, are plotted on Figure 19. The basic shape of the curve is the same as obtained for the others and the close coincidence of the two curves indicates essentially no difference between the plugging effect of living and dead bacteria cells.

Figure 19 Permeability Ratio vs Input Volume
For Living and Dead Bacteria Concentrations



Core No.	Ki, Initial Permeability (md)	
⊙ 12	181.0	Living Bacteria
◇ 3	301.0	Dead Bacteria

Constant Concentration of Bacteria 1.16×10^6/ml

CONCLUSIONS AND RECOMMENDATIONS

1. All cores tested showed the same general plugging trend. During the first portion of each water injection run plugging occurred at a high rate, as shown by the rapid decrease in permeability. This was due to the fact that the small flow channels of the core were easily plugged. During the middle portion of each run the plugging rate decreased, during which time bacteria accumulated in the larger sized channels. When the accumulation of bacteria cells had sufficiently reduced the effective channel size the plugging rate again increased until the flow of injection water practically ceased as the core permeability declined.

2. It was impossible to distinguish any significant difference in the nature of plugging due to variations in initial core permeability. For the range of permeabilities tested the rate and extent of plugging were independent of the permeability. The reason for this behavior may lie in the fact that all cores were taken from the same formation and had a similar textural structure.

3. Variation in bacteria concentration had a marked effect on plugging rate. Decreased concentrations resulted in a lower degree of plugging at any given input volume. However, a ten-fold reduction in concentration did not increase by ten-fold the injection volume to any given degree of plugging.

4. Bacteria penetrated the full length of all cores (up to 9 centimeters). Runs made with the higher concentrations of bacteria showed more effective plugging in the first sections of the cores, while runs with the lower concentrations showed more favorable conditions for the penetration of bacteria cells deeper into the cores.

5. No difference was observed in the plugging characteristics of dead and living bacteria cells.

6. An unusual phenomena was observed during the initial runs. The water contained dissolved air and when the pressure dropped inside the core, air came out of solution and caused plugging at the outflow end of core, augmenting the characteristics of plugging by bacteria. This problem was eliminated by using a water source cylinder with a free running piston between the injection water and air pressure source. It must be noted that the air plugging problem was discovered in the first place only because the cores were equipped with pressure taps and a pressure profile could be obtained. Consequently, some doubt is thrown upon the reliability of initial permeabilities established in research work using cores with only inlet and outlet pressure indicators.

The research work reported herein has of necessity studied only two variables, permeability and concentration

of bacteria, in the search to define the nature of plugging by bacteria in porous systems. The results obtained make additional work in this field appear most appealing, particularly consideration of the variables of formation type, lower bacteria concentrations, and injection rate.

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A P P E N D I X

Table I
Physical Characteristics of Cores

Core No.	$K_{initial}$ (mds)	Length (cm)	T_1^*(cm)	T_2^*(cm)	T_3^*(cm)
1	64.2	9.20	2.30	4.60	6.90
2	68.2	9.00	2.25	4.50	6.75
3	301.0	7.60	1.90	3.80	5.70
4	243.0	7.80	1.95	3.95	5.90
5	168.5	7.95	2.15	4.00	6.05
6	123.0	7.70	2.10	3.90	5.90
7	285.0	7.70	1.95	3.85	5.80
8	282.0	8.10	2.20	4.20	6.05
9	131.0	8.20	2.05	4.10	6.15
10	133.4	8.90	2.20	4.40	6.70
11	125.8	7.85	2.00	3.975	5.95
12	181.0	6.95	1.75	3.60	5.35

Cross-sectional area of all cores = 4.91 square centimeters
Average Porosity = 31.2%

****

Table II
Experimental Results - Core No. 1

Time (hrs)	P(psi)	P_1(psi)**	P_2(psi)**	P_3(psi)**	Flow Rate (cc/sec)
Initial ***	34	25.5	17.0	8.5	0.1176
19		26.2	22.6	19.1	0.0834
24		27.1	23.7	19.8	0.0666
47		29.7	27.4	25.3	0.040

Table III
Experimental Results - Core No. 2

Initial	40	30.0	20.0	10.0	0.150
2		24.0	18.8	13.7	0.1296
3		19.7	17.0	13.4	0.0917
5		21.2	20.0	18.8	0.0358
9		22.2	21.2	20.2	0.0122

Concentration of Bacteria:
13.6×10^6/ml

* Distance of pressure taps from input end of core

** Pressures at corresponding pressure taps (T)

*** Initial run with distilled water

**** Used Bacteria: Bacillus Subtilis

Table IV
Experimental Results - Core No. 3

Time (hrs)	P (psi)	P_1(psi)	P_2(psi)	P_3(psi)	Flow Rate (cc/sec)
Initial	* 40	29.1	19.4	9.7	0.784
Start of test		29.1	19.4	9.7	0.784
2		27.8	18.6	9.3	0.667
5		23.9	15.7	7.7	0.55
10		18.9	12.2	5.9	0.472
15		13.1	8.2	3.8	0.33
20		5.8	3.3	1.2	0.18
25		2.8	1.6	0.6	0.1033
30		1.3	0.5	0.2	0.07

Concentration of Bacteria: 1.16×10^6/ml

Table V
Experimental Results - Core No. 4

Initial	40	28.6	18.8	9.3	0.617
Start of test		28.6	18.8	9.3	0.617
2		26.4	17.4	8.3	0.57
5		23.0	14.7	6.6	0.508
10		17.4	10.8	4.8	0.392
15		10.0	5.7	2.6	0.2835
20		6.3	3.5	1.5	0.20
35		2.3	0.9	0.4	0.0866

Concentration of Bacteria: 1.16×10^6/ml

Table VI
Experimental Results - Core No. 5

Initial	40	28.2	19.2	8.6	0.42
Start of test		28.2	19.2	8.6	0.42
5		25.8	17.3	7.4	0.336
10		23.8	15.8	6.5	0.313
15		21.6	14.4	5.8	0.287
20		18.6	12.2	4.8	0.254

Concentration of Bacteria: 1.16×10^6/ml

* Beginning of actual test with bacteria after the elimination of swelling effect.

Table VII
Experimental Results - Core No. 6

Time (hrs)	P(psi)	P_1(psi)	P_2(psi)	P_3(psi)	Flow Rate (cc/sec)
Initial	40	27.2	18.6	9.0	0.3166
Start of test		27.2	18.6	9.0	0.3166
2		26.1	17.9	8.4	0.3000
5		23.8	16.1	7.3	0.2718
10		19.6	13.4	5.8	0.230
14		15.4	10.5	4.7	0.1917

Concentration of Bacteria: 1.16×10^6/ml

Table VIII

Experimental Results - Core No. 7

Initial	40	29.8	19.6	9.4	0.734
Start of test		29.8	19.6	9.4	0.734
2		26.3	16.8	7.8	0.55
5		23.9	14.6	6.5	0.484
10		19.8	11.3	4.8	0.384
15		16.5	8.9	3.5	0.3
20		13.2	6.5	2.3	0.2266

Concentration of Bacteria: 11.6×10^6/ml

Table IX
Experimental Results - Core No. 8

Initial	40	27.7	18.0	9.4	0.69
Start of test		27.7	18.0	9.4	0.69
5		26.2	17.2	8.5	0.634
15		25.2	16.2	7.7	0.60
20		24.1	15.3	7.1	0.562

Concentration of Bacteria: 0.116×10^6/ml

Table X
Experimental Results - Core No. 9

Time (hrs)	P(psi)	P_1(psi)	P_2(psi)	P_3(psi)	Flow Rate (cc/sec)
Initial	40	26.7	18.6	9.4	0.3165
Start of test		20.7	13.8	6.9	0.1891
1		13.8	9.2	4.6	0.1082
2		11.4	7.6	3.8	0.0917
6		7.5	5.0	2.5	0.0566
13		6.3	4.2	2.1	0.045
17		5.1	3.4	1.7	0.0358
31		2.6	1.4	0.7	0.01418

Concentration of Bacteria: 13.6×10^6/ml

Table XI
Experimental Results - Core No. 10

Initial	40	29.2	19.6	9.3	0.2976
Start of test		28.2	19.2	9.2	0.2665
2		25.9	17.5	8.0	0.2165
5		20.3	14.2	6.2	0.1642
10		16.3	12.1	4.7	0.1333
30		6.3	4.2	1.7	0.0516
35		2.6	1.4	0.7	0.0175
40		1.1	0.6	0.3	0.0075

Concentration of Bacteria: 1.16×10^6/ml

Table XII
Experimental Results - Core No. 11

Initial	40	29.2	17.9	7.8	0.3176
Start of test		27.6	17.4	7.3	0.2966
3		22.0	13.8	5.7	0.2114
5		17.8	11.3	4.3	0.1809
10		13.2	8.2	2.8	0.1268
17		9.9	5.8	1.8	0.0917
40		3.7	1.7	0.7	0.030
50		1.3	0.7	0.3	0.020

Concentration of Bacteria: 0.116×10^6/ml

Table XIII
Experimental Results - Core No. 12

Time (hrs)	P(psi)	P_1(psi)	P_2(psi)	P_3(psi)	Flow Rate (cc/sec)
Initial	40	29.3	19.8	9.2	0.516
Start of test		29.3	19.8	9.2	0.516
2		27.8	18.4	8.3	0.4536
5		26.5	17.4	7.4	0.412
10		22.2	14.4	6.1	0.3566
15		18.0	11.4	4.7	0.310

Concentration of Bacteria: 1.16×10^6/ml

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